Rapid Thermal Technologies for High Efficiency Silicon Solar Cells

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Abstract:
This paper shows that rapidly formed emitters (≤ 6 min) in a conveyor belt furnace or 3 minutes in an RTP system, in conjunction with a screen-printed (SP) RTP Al-BSF and passivating oxide formed simultaneously in 2 minutes can produce high efficiency cells with no surface texturing, point contacts, or selective emitter. It is shown for the first time that an 80 Ω/☐ emitter and SP Al-BSF formed in a high throughput belt furnace can produce 19% FZ cells, 18.4% MCZ cells and greater than 17% CZ cells with photolithography (PL) contacts. Using PL contacts, we also achieved 19% efficient cells on FZ, >18% on MCZ, and ~17% boron-doped CZ by emitter and SP Al-BSF formation in less than 10 minutes in a single wafer RTP system. Finally, a manufacturable process with 45 Ω/☐ emitter and screen-printed (SP) Al-BSF and Ag contacts formed in the conveyor belt furnace gave 17% efficient cells on FZ silicon. Compared to the photolithography cells, the SP cell gave ~2% lower efficiency along with a decrease in J_{sc} and fill factor (FF). This loss in performance is attributed to a combination of the poor blue response, higher series resistance and higher contact shading in the SP devices

Introduction
Low-cost and high-efficiency are the keys to large-scale acceptability of photovoltaic (PV) systems. The cost break down of current Si PV modules reveals that wafer, cell processing, and module assembly account for approximately 45%, 25% and 30% of the module cost, respectively [1]. The cost of silicon wafer can be reduced by low-cost solar grade polysilicon feedstock material, increased wafer size, reduced kerf losses during slicing, and thinner substrates. However, the single crystalline CZ silicon and cast multi-crystalline silicon accounts for more than 75% of the PV cells fabricated today. The lower efficiency realized from CZ substrates compared to FZ wafers has been partly attributed to defects and light induced degradation due to the presence of B_i and O_i [2]. Glunz et al [3] have shown that cell processing involving prolonged heat treatments for CZ substrates can reduce the lifetime degradation and produce efficiency improvement of around one percent absolute. However conventional furnace processing can take more than one hour at 850-900°C for phosphorus diffusion alone. This could limit the throughput of a manufacturing line. The purpose of this study is to develop and demonstrate rapid technologies for emitters without sacrificing cell efficiency on single crystal silicon materials, including FZ, CZ, and magnetic CZ silicon.

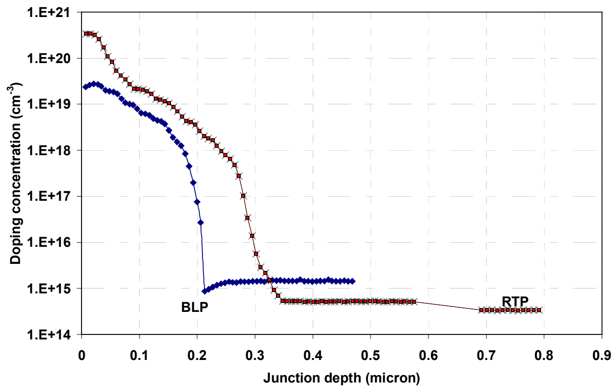

Fig. 1: Doping profiles of 80-90 Ω/☐ emitters formed in a belt furnace in 6-min and in an RTP system in 3 minutes.

Device Fabrication
Our approach towards rapid thermal technologies for high efficiency cells involves (1) rapid emitter formation by belt furnace processing (BFP) and rapid thermal processing (RTP), under tungsten halogen lamps instead of conventional infrared furnace processing (CFP), and (2) use of screen-printed (SP) aluminum followed by 2 minutes RTP for simultaneous back surface field (BSF) and *in-situ* front oxide formation. In this study the belt emitter was formed at 925°C in 6 min, RTP emitter was formed at 880°C in 3 minutes in a single wafer RTP system and a conventional furnace emitter was formed at 865°C in about 1 hour. After the emitter formation, Al was screen-printed on the back and fired in an RTP system at 850°C for 2 min with oxygen ambient. This resulted in simultaneous formation of excellent Al BSF and front oxide passivation. Cells were fabricated with SP as well as photolithography contacts. The photolithography cells had only one masking step involving lift-off. No surface texturing, point contacts or selective emitter were used to keep the cell design very simple. In the case of screen-printed cells Ag contacts were fired through the single layer PECVD SiN AR coating.

Results and Discussion
The emitter profiles for BFP and the RTP for the 80-90 Ω/☐ are shown in Fig. 1. As revealed by Fig. 1,

the junction formed by the RTP is deeper (0.33 µm with > 1E20 cm^{-3} surface concentration) than that formed by the BFP (0.23 µm with < 1E20 cm^{-3} surface concentration). This is partly attributed to the lower wafer temperature compared to the set temperature in the belt furnace. Table 1 shows the light IV data for the RTP, BFP and CFP cells fabricated on FZ silicon. It is quite clear that rapid technologies using belt furnace or RTP system for emitter formation produce essentially the same efficiency (19%) as the CFP cells with lengthy emitter formation. Table 1 shows a 1.1-mA/cm^2 difference in J_{sc} and 5 mV difference in V_{oc} between the BFP and RTP cells on FZ silicon. However, the efficiencies are 19% for both the cells (independently confirmed by Sandia National Laboratories).

Table 1: Electrical output parameters of CFP, RTP and BFP solar cells.

Cell ID	V_{oc} (mV)	J_{sc} (mA/cm^2)	FF (%)	η (%)
BFP-PL-FZ	636	37.3	80.2	19.0
RTP-PL-FZ	641	36.2	81.9	19.0
CFP-PL-FZ	634	37.1	80.5	18.9
BFP-SP-FZ	629	34.9	77.4	17.0
BFP-PL B-doped CZ	610	36.1	79.5	17.5
RTP-PL B-doped CZ	608	35.1	79.0	16.9
BFP-MCZ-PL	636	35.6	81.3	18.4

IQE and reflectance curves in Figure 2 reveal that the difference in the short circuit current is due to slightly higher front surface reflectance of the RTP cell. This is attributed to higher phosphorus surface concentration of the RTP emitter, which led to a slightly thicker passivating oxide, degrading the reflectance.

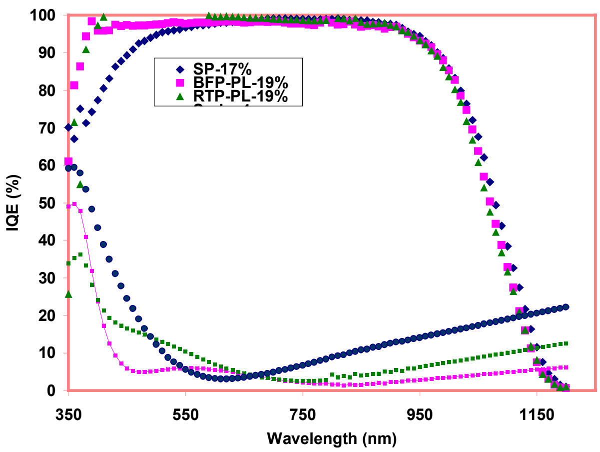

Fig. 2: IQE and hemispherical reflectance of 19% efficient BFP-PL and RTP-PL and 17% SP cells.

Table 1 shows that the FZ cell with 45 Ω/□ belt emitter with screen-printed Ag contacts gave an efficiency of 17%. This 2% absolute reduction in efficiency compared to the counterpart photolithography cells is associated with 7 mV decrease in V_{oc}, 2.4 mA loss in J_{sc}, and 0.028 reduction in FF. Detailed modeling [4] has shown that the 2% efficiency loss for screen-printed cells can be attributed to poor metal conductivity, high contact resistance (0.2%), high surface recombination (0.4%), sheet loss (0.1%), emitter doping (0.3%), AR coating and absorption in SiN (0.3%) and higher grid shading (0.5%).

Table 1 also shows that a PV grade CZ material gave efficiencies of ~17% for both BFP and RTP cells with photolithography contacts. This 2% lower efficiency of CZ cells compared to FZ cell is attributed to lower bulk lifetime. In order to overcome this deficiency, a crucible grown magnetic CZ was used. This material gave 18.4% efficient cells with belt furnace processing and PL contacts or a 1.4% higher efficiency compared to CZ cells. Thus a combination of rapid technologies and magnetic CZ silicon can produce lower-cost high- throughput high-efficiency cells.

Conclusions

This paper shows that rapidly formed 80 Ω/□emitters in less than 6 minutes in the hot zone of a conveyor belt furnace or 3 minutes in an RTP system can produce 19% efficient cells with no surface texturing, point contacts, or selective emitter. We also achieved 19% efficient cells on FZ by emitter and SP Al-BSF formation in less than 10 minutes in the RTP system. Finally SP manufacturable cells with 45 Ω/□ emitter and SP Al-BSF formed in the conveyor belt furnace gave 17% efficient cells on FZ silicon. The SP cell gave ~2% lower efficiency along with a decrease in J_{sc} and fill factor (FF). This is attributed to the poor blue response, higher series resistance and higher contact shading in the screen-printed devices.

References

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